Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 96, No. 3, December 1987, pp. 249–257

Seasonal variation of the salinity in the Zuari estuary, Goa, India

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MS received 13 April 1987; revised 24 August 1987

Abstract. The annual salt budget of the Zuari is examined. The characteristics of the estuary differ markedly from the low run off season during November–May to the heavy run off period of the southwest monsoon from June to October. During November–May the estuary is vertically mixed and the two processes controlling the transport of salt are run off induced advective transport out of the estuary, and tidally induced diffusive transport into the estuary. The magnitude of the latter is about 20% larger, leading to a salinity rise in the estuary. The diffusion coefficient has been estimated to be $233 \pm 101\ \mathrm{m^2/sec}$. With the onset of the southwest monsoon, the run off increases dramatically, and the estuary loses about 75% of its salt during the first two months of the season. About 2/3 of this loss is recovered in the next two months when the run off decreases. Because the estuary is partially stratified during June–October, gravitational circulation is expected to play a role in addition to tidal diffusion and run off. The magnitude of its contribution has, however, not yet been determined.

Keywords. Estuary; salt budget; seasonal variation; vertically mixed; monsoon region; west coast of India.

1. Introduction

The Zuari estuary is located on the west coast of India and joins the Arabian Sea near the port city of Marmagao (figure 1). The salinity distribution in this estuary shows that during May, just before the onset of the southwest monsoon, tidally averaged salinities well in excess of 1 ppt are observed upto 40 km from the mouth. By July the salinity drops dramatically, and is generally < 1 ppt upstream of 20 km from the mouth of the estuary. The salinity throughout the length of the estuary increases continuously from October to May.

This seasonal cycle is typical of the shallow and narrow estuaries on the west coast of India, which comes under the influence of the atmospheric monsoon circulation and experiences a spell of heavy precipitation of the order of 250 cm during June–October. During November–May, the dry season, total precipitation is < 10 cm. These estuaries have not been studied much, and virtually nothing is known about the transport processes that control their seasonal salinity cycle. In the present paper we have attempted to synthesize the available data from the Zuari estuary to determine the principal constituents of the seasonal salt budget of the estuary.

2. Zuari — a physical description

Figure 1 gives the location of the Zuari estuary. The variation of the mean centreline depth in the estuary is given in figure 2a and that of mean cross-sectional

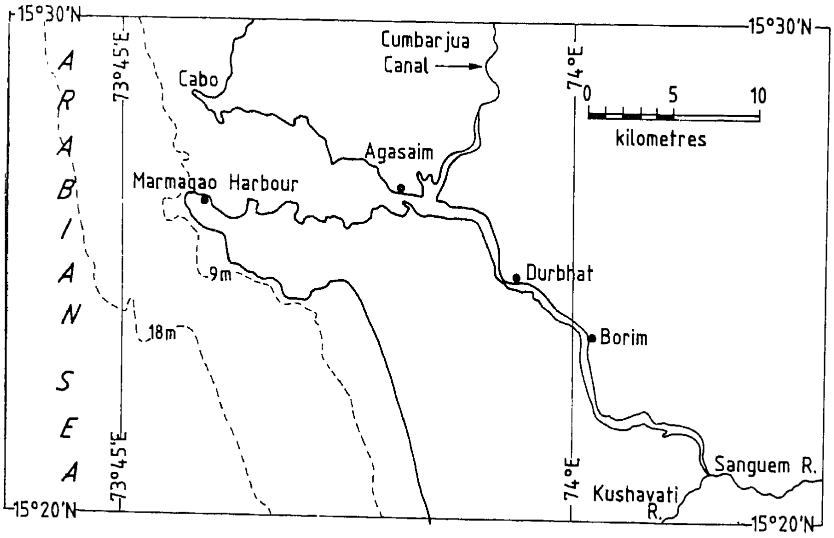

Figure 1. The Zuari estuary.

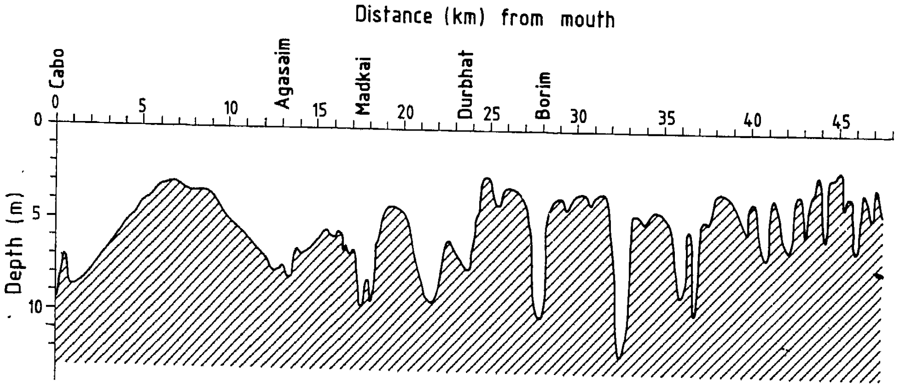

Figure 2a. Centreline mean depth (m) profile of the Zuari.

area is given in figure 2b. The average depth upto 40 km from the mouth is approximately 5 m. The bottom topography is marked by a few trenches as deep as 10 m. The cross-sectional area of the estuary decreases exponentially. The decrease is more rapid in the first 20 km from the mouth.

Joining the estuary at about 15 km from the mouth is the Cumbarjua Canal which connects the Zuari to another estuary, the Mandovi. The width of the canal varies between 100 and 320 m and its cross-sectional area decreases from 820 m^2 near the Zuari to 370 m^2 at the Mandovi (Mehta *et al* 1983). Since the cross-sectional area of the canal is small compared to the area of the Zuari at the point where the two join, and also since the Canal is not a significant source of fresh water, we have ignored its influence in the discussion here.

The tides recorded at the Marmagao harbour are mixed with a marked diurnal inequality (Indian Tide Tables 1985). The range during the spring tides can be as

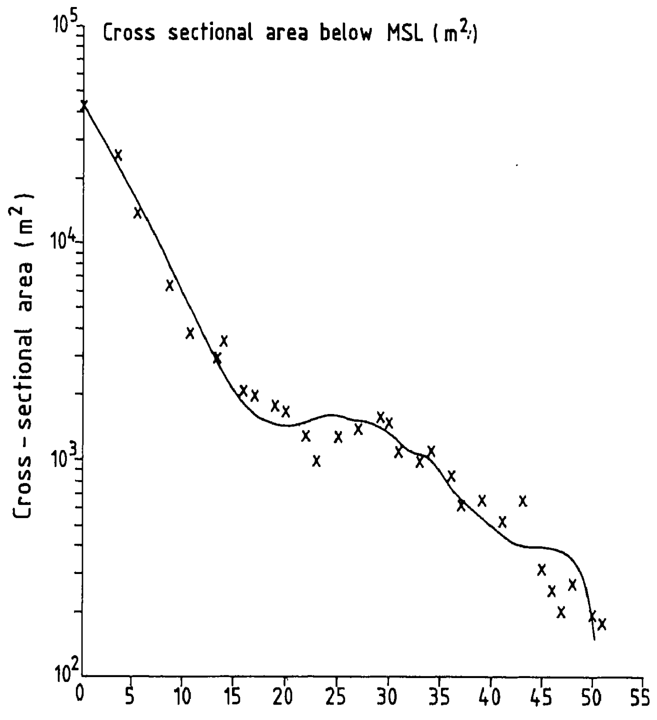

Figure 2b. Variation of mean cross-sectional area (m^2) in the Zuari. Horizontal axes give distance (km) from the mouth of the estuary.

high as 2·3 m. The nature of variation in the phase and range of the tide along the estuary is not known.

The two main rivers Kushavati and Sanguem, contributing freshwater run off to the Zuari were gauged during the southwest monsoon seasons of 1963, 1964 and 1966. The run off in the Zuari inferred from these data is given in figure 3 (Das *et al* 1972). Virtually all the rainfall in the catchment area of the Zuari occurs during June–October. The rainfall shows marked time variability corresponding to the break and active phases of the southwest monsoon. Consequently, the run off in the estuary can fluctuate from 100 m^3/sec to 400 m^3/sec over a period of few days. The Zuari has not been gauged during the dry spell from November to May, the period during which the catchment area receives $<$ 10 cm of rainfall. The run off in the river is believed to decrease monotonically from November till the onset of the next southwest monsoon.

The vertical variation in salinity undergoes marked changes from season to season. At Agacaim, for example, Cherian *et al* (1975) report $<$ 0·5 ppt salinity variation from surface to bottom during April, the vertically averaged salinity being 34·5 ppt. Towards the end of September the surface to bottom difference in salinity is almost 7 ppt, and the average salinity of the water column is 26 ppt. Cherian *et al* (1975) further report that the surface to bottom change in salinity at Borim is around 1 ppt in January and over 5 ppt in September, the vertically averaged salinities in January and September being 23 ppt and 10 ppt respectively. These

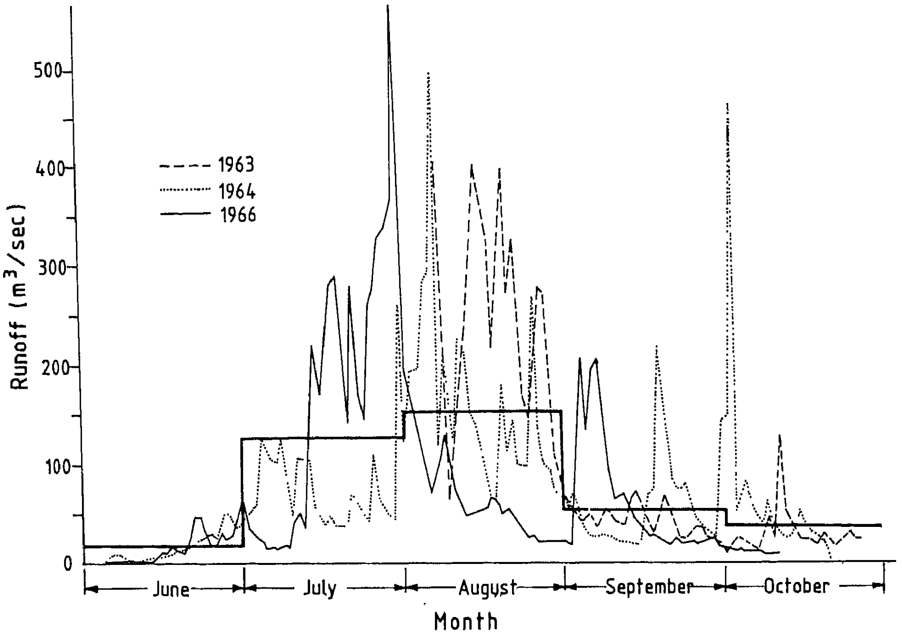

Figure 3. Run off (m^3/sec) in the Zuari estuary during the southwest monsoon seasons of 1963 (----), 1964 (····) and 1966 (——). The monthly-mean run off, computed by averaging the run off for these three years, is shown by (——).

figures suggest that the character of the estuary changes from the dry season (November to May) to the wet season (June to October). This point is highlighted from the following consideration. The intertidal volume of the Zuari is around 90×10^6 m^3. The fresh water contribution to the intertidal volume is thus $< 0{\cdot}5\%$ during the dry season when the run off is < 10 m^3/sec. The mean run off during August is 150 m^3/sec. Hence the run off contribution is $> 7\%$ of the intertidal volume. When, during an active phase of the monsoon, the run off exceeds 400 m^3/sec, the same contribution would exceed 20%. Such high rainfall episodes generally last only a few days and are distributed at random over a season. During such an episode, a rapid variation with time in the behaviour of the estuary is expected.

In summary, the Zuari shows two distinct conditions. It is vertically mixed with little time variability during the dry period of November–May. The estuary is partially stratified with large time variation due to fluctuations in run off during the southwest monsoon season.

3. Seasonal salt budget and horizontal diffusion coefficient

From November 1977 to September 1978 the salinity distribution in the Zuari was recorded during one tidal cycle once every month. The vertical averages of salinity based on this survey have been reported earlier by Qasim and Sen Gupta (1981). The data from the same survey are used in figure 4 to describe the annual cycle in

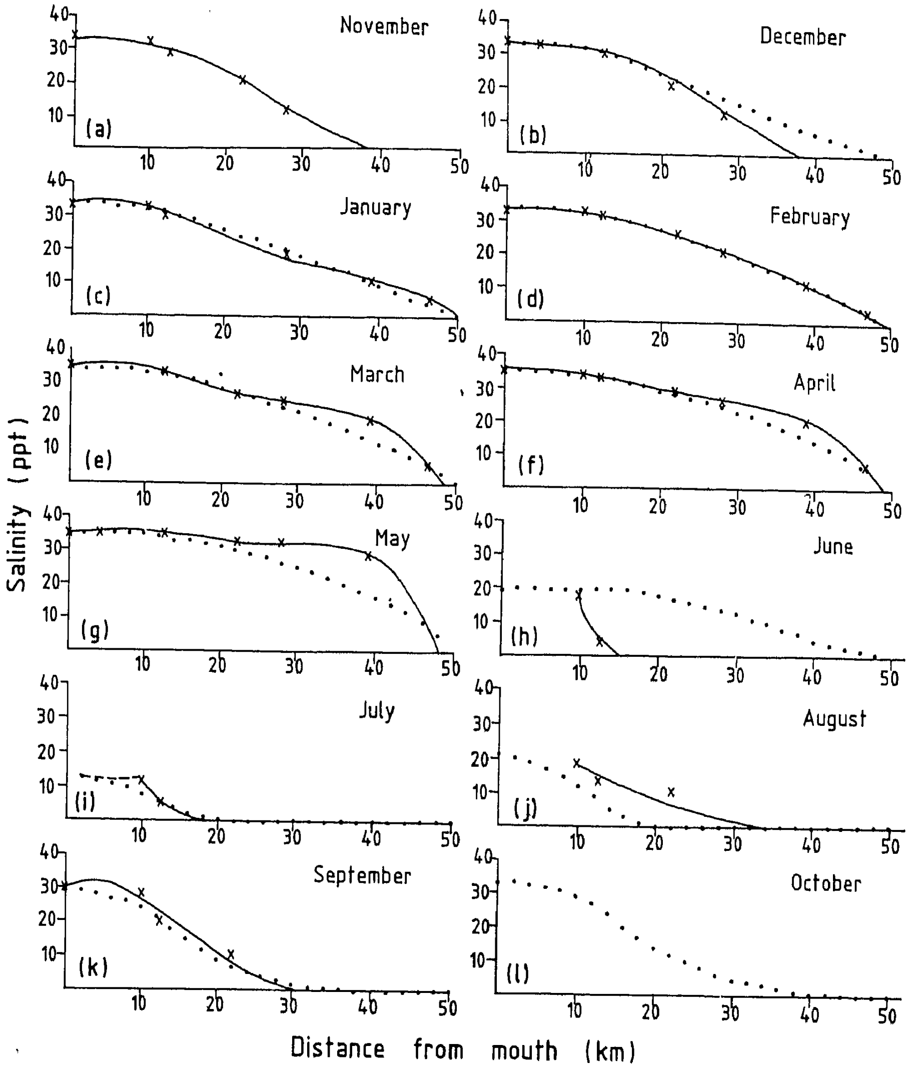

Figure 4. Annual cycle of salinity distribution in the Zuari. The horizontal axes give distance from the mouth. The observed values are denoted by crosses (x). Thin line gives a polynomial fit $S(x)$ to the observations (····) gives the salinity simulated by the model described in §4.

the axial salinity distribution. As day-to-day or week-to-week variations in the Zuari are small during November–May, we can look at each one of the figures 4 a-g as representative for that month. The same, however, cannot be said about figures 4 h-k. For reasons discussed earlier, large variations in the characteristics of the estuary are expected from week to week during June–September. Hence significant scatter around the data plotted in figures 4 h-k is expected if observations are repeated.

In figure 4 we have also plotted curves which are polynomial least square fits to the observations. These curves give, for each month, salinity S as a continuous function of x, the upstream distance from the mouth of the Zuari. The total salt in the estuary, S_{tot}, is given by

$$S_{\text{tot}} = \int_0^{x} S(x)\ A(x)\ \mathrm{d}x, \tag{1}$$

where A is the cross-sectional area. The upper limit of the integral is the far upstream end of the estuary where S vanishes. In figure 5 we have plotted the annual variation in S_{tot} together with the average monthly-mean run off in the Zuari. The run off values for June–October are based on the data in figure 3. During November–May the monthly-mean run off has been assumed to decrease linearly with time from 15 m^3/sec in October to 3 m^3/sec in May.

As seen from figure 5, S_{tot} increases continuously from November to May, the rate of increase being approximately 70 (ppt m^3)/sec. The mean run off and the salinity at the mouth of the estuary during the same period are 9 m^3/sec and 34·2 ppt respectively. Hence the average advective transport of salt out of the estuary due to run off during the period is about 300 (ppt m^3)/sec. As the estuary is well mixed in the vertical during the dry season, we expect the contribution of gravitational circulation to the salt transport into the estuary to be negligible. Hence, to explain the observed increase in S_{tot}, there has to be a tidally-induced diffusive transport of about 370 (ppt m^3)/sec into the estuary. Thus the magnitude of the advective and that of the diffusive transport is about 5 times the rate of change of S_{tot}. The variation of S_{tot} during the southwest monsoon is far more rapid. The estuary loses about 75% of its salt in the first two months of the wet spell. During the next two months when the run off decreases, about 2/3 of this loss is recovered.

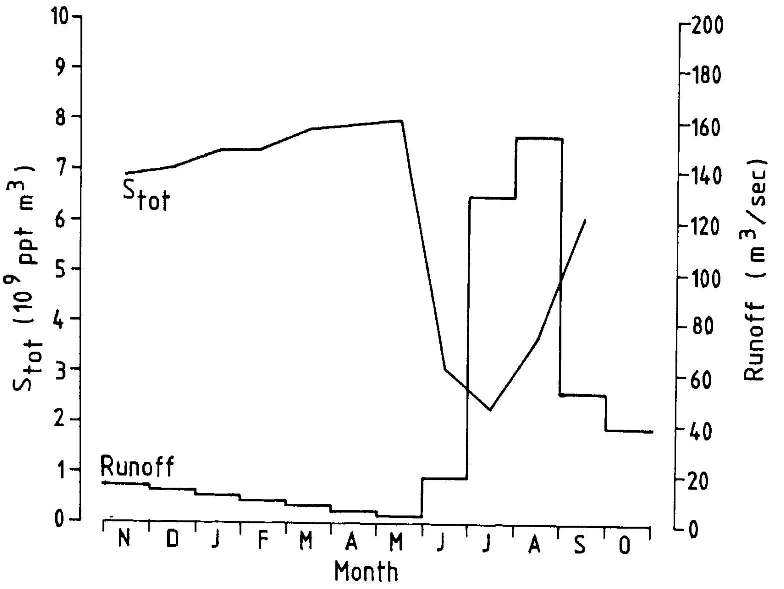

Figure 5. Annual cycles of S_{tot} (see equation (1)) and monthly-mean run off (m^3/sec).

During November–May, the dry season, it is reasonable to assume that at any point x along the estuary, the following one-dimensional advection-diffusion equation holds

$$\frac{\partial}{\partial t}\int_{x}^{\infty} S(x')\, A(x')\, \mathrm{d}x' = KA\frac{\partial S}{\partial x} + RS. \tag{2}$$

Here K, R and t are the axial diffusion coefficient, run off and time respectively. Each of the terms, except K, in the above equation can be estimated by using the data in figures 2b, 4 and 5. Hence the relation can be used to compute K. A steady state version of this procedure has been used in Stommel (1953). We have computed K every 5 km up to 40 km upstream of the mouth. The left side of the equation was estimated using $S(x)$ for two consecutive months. The averages of $\partial S/\partial x$, S and R for these two months were used on the right side. The results are plotted in figure 6. As seen from the figure, K does not show any systematic variation with distance nor with time. The average and the standard deviation of all the values of K were found to be 233 m^2/sec and 101 m^2/sec respectively. A linear regression, $K = K_0 + K'x$, gave K_0 and K' equal to 244 m^2/sec and 0·88 (m^2/sec)/km respectively.

4. A one-dimensional advection-diffusion model study

To examine the extent to which the above one-dimensional advective-diffusive balance applies to the annual salinity cycle in the Zuari, we modelled S using the equation obtained by differentiating (2) w.r.t. x. The second order PDE was solved using an implicit alternating direction finite difference method with increments in t and x set equal to 0·1 day and 2 km respectively. The simulation was started on November 16 with $S(x)$ given in figure 4a. The observed salinities at the mouth

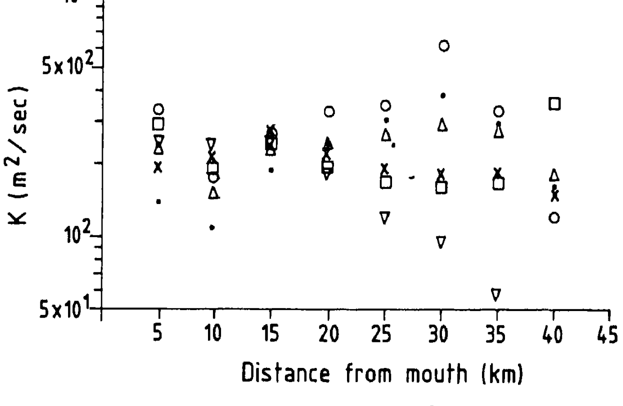

Figure 6. Horizontal diffusion coefficient K (m^2/sec), computed by using equation (2). Data for two consecutive months were used to estimate terms in the equation November-December (▽), December-January (□), January-February (×), February-March (△), March-April (●) , and April-May (○).

$x = 0$ km, were used as one boundary condition. At the other boundary, $x = 50$ km, the salinity was set equal to zero. The diffusion coefficient was taken to be 240 m^2/sec, and the run off in figure 5 was used.

The result of the simulation on the 15th of each month (every month was assumed to be of 30 days) is plotted in figure 4. The simulation shows that the overall pattern of salinity variation is fairly well reproduced during the dry season. This result justifies the assumption in the model that the estuary is of a vertically and laterally mixed-type during this season. The model did not fare well during the southwest monsoon. The likely reasons are that during the southwest monsoon, because the estuary is partially stratified, gravitational circulation will be contributing to the salt transport. This has not been taken into account in the model. Secondly, the model has not considered the contribution of the wind driven circulation in the estuary. This contribution is expected to be important during the southwest monsoon when strong westerlies exert stress directed upstream of the estuary. Lastly, it is worth noting that the observed salinity field for a month given in figure 4 really represents the condition that existed on a particular day. During the southwest monsoon, when run off, windstress, etc. are highly variable, it is unrealistic to expect that the climatic model used here would be able to simulate conditions for a particular day.

5. Conclusions

The Zuari estuary, a typical shallow, narrow estuary on the west coast of India shows distinct characteristics in the wet season (June-September) of the southwest monsoon and the dry season during October-May.

During the dry season the estuary is well mixed vertically and experiences a temporal increase in salinity throughout its length. The two transport processes controlling the salt budget of the estuary during this season are the run off induced advection of salt out of the estuary, and the tidally induced diffusion into the estuary. The latter is about 20% larger of the two processes and leads to a net upstream movement of salt. The diffusion coefficient has been estimated to be 233 ± 101 m^2/sec.

During the wet spell of the southwest monsoon, the run off in the estuary increases rapidly. As a result the estuary loses about 75% of its salt in approximately two months. During the following two months, when the run off decreases, about 2/3 of the lost salt is recovered. The transport of salt into the estuary is partly due to tidal diffusion, and partly due to gravitational circulation. The magnitude of the latter is not known, but is expected to be significant because the estuary is partially stratified during this season.

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